## MPRG Research Capabilities

The MPRG has significant research expertise in the areas of spread-spectrum systems, mobile radio propagation and interference rejection techniques. As a result, the MPRG possesses a combination of facilities and experience which is uniquely suited to addressing the problem of spectrum sharing within AVM systems.

In this section we describe the research capabilities of the MPRG. First we describe the general research capabilities of the MPRG. Next, we describe the specific research expertise in the MPRG which is applicable to the work described in this proposal. Finally, we include brief biographies of the three principle investigators for this project.

## A. MPRG Research Facilities

### *The Bradley Department of Electrical Engineering*

The Mobile and Portable Radio Research Group (MPRG) is a part of The Bradley Department of Electrical Engineering, one of the largest electrical engineering departments in the nation, with 60 full-time faculty members, and a broad range of graduate research and study programs. The Department produces approximately 250 bachelor's degrees each year, and is consistently ranked in the top 20 programs. Virginia Tech is one of the few universities that offers courses in mobile and portable radio as a regular part of the curriculum. The Bradley Department of Electrical Engineering conducts about 130 research projects each year with an annual research budget of approximately ten million dollars. The Department has approximately 550 graduate students in electrical engineering.

### *The Mobile and Portable Radio Research Group*

The MPRG was founded in 1990 to conduct research in emerging wireless communication technologies. The group has research, teaching and service missions which are national in scope, and is a leading producer of professionals for the wireless communication industry. The group consists of three full-time faculty, three support staff and approximately thirty graduate students. Major MPRG research thrusts include:

- Measurement and analysis of propagation characteristics for wireless channels.
- Site-specific prediction of propagation characteristics.
- Simulation and analysis of wireless communications systems using real-world channel models.
- Development of signal processing algorithms for interference rejection, antenna steering, error correction and fast synchronization.

Since its inception, the MPRG has conducted over $2.6 million in funded research. Core funding is provided by the MPRG Industrial Affiliates Foundation, a coalition of 14 major corporations in the wireless field. MPRG Industrial Affiliates include: Apple Computer, AT&T, Bell Communications Research (BellCore), BellSouth, BNR, Ericsson-GE Mobile Communications, The Federal Bureau of Investigation (FBI), Grayson Electronics, GTE, MCI, Motorola, Rockwell, Southwestern Bell, Telisys Technologies Laboratory, and US West. The MPRG prepares quarterly research reports for its industrial affiliates members and promotes aggressive technology transfer through frequent visitation. Most industrial affiliate members have hired one or more MPRG graduates.

The MPRG also conducts specific funded research for individual sponsors. Currently, 14 organizations sponsor funded research with the MPRG, including the Advanced Research Projects Agency (ARPA). Within the last year, MPRG has received two prestigious

awards from the National Science Foundation: a Presidential Faculty Fellowship, and a Research Initiation Award.

### *Research Facilities*

The MPRG possesses outstanding facilities for computing, RF measurement, and DSP algorithm development. The MPRG operates a network of 12 SUN SPARC 10 workstations with access to INTERNET and a larger departmental network. The MPRG's facilities for wireless propagation measurement are among the best available at any academic facility. MPRG researchers have applied for three patents based on measurement work. The current generation of propagation measurement equipment was constructed entirely by MPRG researchers. The system employs a spread-spectrum sliding correlator receiver for measurement of the channel power delay profile. The system features:

- 4 nanosecond time resolution.
- Measurement frequencies ranging from 100 MHz to 25 GHz.
- Disk storage of measured data for further analysis, and spectrum analyzer and oscilloscopes for immediate frequency and time domain analysis of measured data.

### *MPRG Software Tools*

MPRG researchers have access to tools for technical word processing (Framemaker), plotting (PVWAVE), software development (C and C++), and signal processing (Xmath and Matlab). In addition, MPRG researchers have developed several software packages for wireless communication research. These products are made available to the wireless community through Virginia Tech's intellectual properties division. Over 100 copies of MPRG software are now in use in academic and industrial research labs including SIRCIM, SMRCIM, and BERSIM, described in Section III B.

### *MPRG Outreach and Technology Transfer*

The MPRG works to aggressively transfer knowledge to industry, and develop new products and services. All research results are disseminated to industrial affiliates through quarterly mailings of research reports. In addition, the MPRG newsletter *The Propagator* reaches an audience of over 4000. The MPRG holds an annual research symposium on wireless and personal communications. The third and most recent, held in June 1993, featured twenty one high quality research papers and was attended by over 150 wireless professionals. The proceedings from this symposium will be published in book form by Kluwer Academic Publishing.

## B. Research In Mobile Spread-Spectrum Systems

In recent years, the MPRG has been an active contributor of research in areas with direct application to proposed AVM systems. This include: measurement, simulation and prediction of the mobile communications channel; analysis and simulation of spread-spectrum systems; and research into advanced techniques for interference rejection.

### *Research in Radio Wave Propagation*

Dr. Rappaport founded the MPRG in 1990 and has advised sixteen M.S. and Ph.D. students in the areas of RF propagation, antenna design, signal processing, and capacity analysis. He and his graduate students have developed the first channel modeling software packages (SIRSIM, BERSIM, SMRSIM) for indoor and urban mobile communication systems. He currently serves as PI on a DARPA project which is developing site specific

RF prediction tools that incorporate terrain, building locations, and physical propagation paths. Such information is vital to the analysis, simulation, and design of AVM systems. Sophisticated and realistic channel modeling tools are being created specifically for allowing accurate assessments of the performance of adaptive arrays [Sch92b, Sei93, Tra93, Ho93]. His current research includes the development of novel antenna structures and adaptive array algorithms that will demonstrate the accuracy of the simulation and analysis tools.

***Research in Direct-Sequence Spread-Spectrum***

Dr. Woerner's research has focused on design and evaluation of DS/SS systems for wireless communications. His most important accomplishments have been in pioneering the use of trellis-coded modulation techniques for spread-spectrum communications, and the development of analysis and simulation tools for the evaluation of DS/SS systems.

Dr. Woerner has actively developed analysis and simulation techniques for the evaluation of CDMA systems in real-world environments. Traditionally, analysis of DS/SS systems has relied heavily on approximating all interference as Gaussian. This approximation may not be valid at low bit error rates or in the case of sever near/far problems. Lehnert and Pursley have developed techniques to accurately analyze the effects of multiple access interference and obtain tight performance bounds [Leh87, Leh89]. Dr. Woerner has extended these results to systems with soft decision [Woe92b] and hard decision error correction codes [Woe93c], systems with imperfect power control [Woe92a], and systems with real world multipath channels and RAKE receivers [Cam93a, Cam93b].

Dr. Woerner has also worked on the development of simulation tools which model complex DS/SS systems and channels. The MPRG has developed a Bit Error Rate SIMulator (BERSIM) [Rap91, Tho92], which has been extended to model the IS-95 CDMA cellular standard [Li93a, Li93b]. BERSIM has several advantageous characteristics which include its modular construction that allows the addition of new modules, use of a wide variety of channel impulse response models, and the ability to record bit-by-bit error patterns, which allows for assessment of the effects of burst error events on actual transmitted data.

***Research in Interference Rejection***

Dr. Reed's research has focused on the use of advanced DSP techniques for interference rejection. Linear time dependent adaptive filters were first demonstrated by [Fer81] and later shown by Dr. Reed and graduate students to be very effective in reducing co-channel interference for a variety of non-spread spectrum signals [Ree90a,b, Ree88, Men88, Men89, Men91, Ree87, Ree91, Ree92]. Reed in his Ph.D. dissertation introduced new time-dependent adaptive filtering algorithms for interference rejection, including frequency domain algorithms and blind time-domain algorithms [Ree87]. He also showed the theoretical performance of time-dependent adaptive filters for specific test cases [Ree87, Ree90a, Ree90b]. The first application of time-dependent filtering for enhancing and despreading spread spectrum for reconnaissance applications was proposed in [Ree89].

Several blind algorithms have been developed for time-dependent adaptive filters. The first of these algorithms, the spectral correlation discriminator (SCD), uses a frequency-shifted or conjugated version of the input signal as the training signal [Ree88]. This technique is easily combined with other adaptive techniques to improve performance [Men89, Men91]. Personal experience has shown phase modulated signals corrupted by television interference can be recovered using the SCD compounded with a CMA TDAF when the

SIR is as low as -19 dB. This mixture of time-dependent filtering operations, beginning with robust blind techniques and followed by less robust, but better performing blind TDAF techniques.

Most of the previous work in time-dependent filtering has focused on applying these techniques to reconnaissance applications of non-spectrally efficient signals. Commercial signals are, however, highly spectrally efficient. For instance, the new IS-54 digital cellular signal standard has a roll-off of 0.35. Experiments show that a time-dependent filter placed at the output of a differential demodulator improves the performance of the IS-54 differential demodulator by over that of a conventional adaptive filter [Ree91a]. Results of the test cases using time-dependent filtering show a BER reduced by a factor of six and the MSE reduced by 9 dB over the time-independent filtering for signals distorted by Rayleigh fading. When a co-channel interfering signal is present, the time-dependent filtering process reduces the BER by a factor of two and the MSE by more than 5 dB over the time-independent filtered signal. In a similar test case, where interference was included, the BER improved by a factor of 100 when the interfering signal overlapped the signal-of-interest by 75% for a SIR of 6 dB.

## C. Biographies of Principal Investigators

### *Theodore S. Rappaport*

Theodore S. Rappaport is an associate professor at Virginia Tech and the founder of the Mobile and Portable Radio Research Group (MPRG). Under Dr. Rappaport's direction, the MPRG was formed in 1990 and has grown to include several faculty members, staff members, and over 30 graduate students. The MPRG is guided by 15 affiliated companies and government agencies which provide direction and funding to the group. The goals of the MPRG are to develop future engineers and technologies for the wireless industry and to transfer technology to affiliated companies and sponsors.

Professor Rappaport conducts research in mobile radio communications system design and RF propagation prediction through measurements and modeling. He has authored or co-authored more than 70 technical papers in the areas of mobile radio communications and propagation, vehicular navigation, ionospheric propagation, and wideband communications. He holds several patents for a wideband antenna and is co-inventor of SIRCIM, an indoor radio channel simulator that has been adopted by over 80 companies and universities. In 1990, he received the Marconi Young Scientist Award for his contributions in indoor radio communications and was named a National Science Foundation Presidential Faculty Fellow in 1992. He is a senior editor of the IEEE Journal on Selected Areas in Communication and Fellow of the Radio Club of America. Dr. Rappaport is a registered professional engineer in the state of Virginia.

### *Brian D. Woerner*

Brian D. Woerner received his B.S. degree in computer and electrical engineering from Purdue University in 1986, and his M.S. and Ph.D. degrees from the University of Michigan, in 1987 and 1991 respectively, where he was a Unisys Fellow. Dr. Woerner has also earned a Master's degree in Public Policy from the University of Michigan with an emphasis on telecommunications policy. Since 1991, Dr. Woerner has worked as an Assistant Professor with the Bradley Department of Electrical Engineering at Virginia Tech in Blacksburg, VA. He is an active member of the MPRG. He has received a Research Initiation Award from the National Science Foundation and has been recognized for outstanding teaching. His research interests lie in the field of wireless communications,

particularly in the analysis of modulation, error correction and code division multiple access techniques.

### *Jeffrey H. Reed*

Jeffrey H. Reed is a member of the MPRG at Virginia Tech. His specialty is in applying digital signal processing to communication systems, and he has a particular interest in DSP techniques for interference rejection. Dr. Reed received his BSEE in 1979, MSEE in 1980, and Ph.D. in 1987, all from the University of California, Davis. He received the American Electronics Teaching Fellowship Award while completing his Ph.D. at the University of California, Davis. From 1980 to 1986, he worked for Signal Science, a small consulting firm specializing in DSP and communication systems. During 1982 he was stationed at the National Security Agency. After graduating with his Ph.D. degree, Dr. Reed worked as a private consultant and as a part-time faculty member at the University of California, Davis. In August, 1992, Dr. Reed joined the faculty of the Bradley Department of Electrical Engineering at Virginia Tech.

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Blacksburg, Virginia 24061-0249
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October 20, 1993

Ms. Susan O'Sullivan
North American Teletrac
2999 Oak Road, Suite 724
Walnut Creek, CA 94596

Dear Ms. O'Sullivan:

Please find enclosed three (3) copies of a research proposal entitled "Capacity and Interference Resistance of Spread-Spectrum Automatic Vehicle Monitoring Systems in the 902-928 MHz ISM Band". This proposal was prepared by T. S. Rappaport, B. D. Woerner, and J. H. Reed in the Department of Electrical Engineering.

Please reference Proposal No. 94-0676-10 in all correspondence related to this proposal.

The University, as a non-profit institution, is limited in the amount of funds available to finance this effort. Therefore, we request that an initial advance payment accompany the initiation of any resultant award.

The University appreciates the opportunity to submit this proposal to you. If fiscal or budgetary questions arise, please contact Ms. Garnett S. Linkous at (703) 231-5283. Questions of a technical nature should be addressed to the Principal Investigator.

Sincerely,

H. T. Hurd
Director

HTH:seb
Enclosures
cc: T. S. Rappaport
B. D. Woerner
J. H. Reed
F. W. Stephenson
J. E. Osborne
G. S. Linkous

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October 20, 1993

Mr. Louis Jandrell
Pinpoint Communications, Inc.
2435 North Central Expressway
Richardson, TX 75080

Dear Mr. Jandrell:

Please find enclosed three (3) copies of a research proposal entitled "Capacity and Interference Resistance of Spread-Spectrum Automatic Vehicle Monitoring Systems in the 902-928 MHz ISM Band". This proposal was prepared by T. S. Rappaport, B. D. Woerner, and J. H. Reed in the Department of Electrical Engineering.

Please reference Proposal No. 94-0675-10 in all correspondence related to this proposal.

The University, as a non-profit institution, is limited in the amount of funds available to finance this effort. Therefore, we request that an initial advance payment accompany the initiation of any resultant award.

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October 20, 1993

Mr. Jack Taylor
Part 15 Coalition
9215 Rancho Drive
Elk Grove, CA 95624

Dear Mr. Taylor:

Please find enclosed three (3) copies of a research proposal entitled "Capacity and Interference Resistance of Spread-Spectrum Automatic Vehicle Monitoring Systems in the 902-928 MHz ISM Band". This proposal was prepared by T. S. Rappaport, B. D. Woerner, and J. H. Reed in the Department of Electrical Engineering.

Please reference Proposal No. 94-0677-10 in all correspondence related to this proposal.

The University, as a non-profit institution, is limited in the amount of funds available to finance this effort. Therefore, we request that an initial advance payment accompany the initiation of any resultant award.

The University appreciates the opportunity to submit this proposal to you. If fiscal or budgetary questions arise, please contact Ms. Garnett S. Linkous at (703) 231-5283. Questions of a technical nature should be addressed to the Principal Investigator.

Sincerely,

H. T. Hurd
Director

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Enclosures
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October 20, 1993

Mobile Vision
10585 North Meridian Street
Suite 200
Indianapolis, IN 46290

Dear Ladies/Gentlemen:

Please find enclosed three (3) copies of a research proposal entitled "Capacity and Interference Resistance of Spread-Spectrum Automatic Vehicle Monitoring Systems in the 902-928 MHz ISM Band". This proposal was prepared by T. S. Rappaport, B. D. Woerner, and J. H. Reed in the Department of Electrical Engineering.

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